NOAA Technical Memorandum NMFS-SEFC-50

Environmental Assessment of Buccaneer Gas and Oil Field In the Northwestern Gulf of Mexico, 1975-1980.

VOL. IV-CURRENT PATTERNS AND HYDROGRAPHY OF THE BUCCANEER FIELD AND ADJACENT WATERS

BY

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A report to the Environmental Protection Agency on work conducted under provisions of Interagency Agreement EPA-IAG-D5-E693-EO during 1975-1980.

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Work Unit 2.3.2	Investigations of Surficial Sediments, Suspended Particulates and Volatile Hydrocarbons at Buccaneer Gas and Oil Field Texas A&M University J. Brooks, Ph.D. E. Estes, Ph.D. D. Wiesenburg C. Schwab H. Abdel-Reheim

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FOREWORD

Increased petroleum development of the outer continental shelf (OCS) of the United States is anticipated as the U.S. attempts to reduce its dependency on foreign petroleum supplies. To obtain information concerning the environmental consequences of such development, the Federal Government has supported major research efforts on the OCS to document environmental conditions before, during, and after oil and gas exploration, production, and transmission. Among these efforts is the Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, a project funded by the Environmental Protection Agency (EPA) through interagency agreement with the National Oceanic and Atomospheric Administration (NOAA) and managed by the National Marine Fisheries Service (NMFS), Southeast Fisheries Center (SEFC), Galveston Laboratory, in Galveston, Texas. Initiated in the autumn of 1975, the study was completed in 1980. Its major products have been annual reports disseminated by the National Technical Information Service, data files archived and disseminated by NOAA's Environmental Data and Information Service, and research papers written by participating investigators and published in scientific or technical journals. Results have also been made available through EPA/NOAA/NMFS project reviews and workshops attended by project participants, and various governmental (Federal and State), private, and public user groups. The final product are these milestone reports summarizing the findings of the major investigative components of the study.

Objectives of the project were (1) to identify and document the types and extent of biological, chemical and physical alterations of the marine ecosystem associated with Buccaneer Gas and Oil Field, (2) to determine specific pollutants, their quantity and effects, and (3) to develop the capability to describe and predict fate and effects of Buccaneer Gas and Oil Field contaminants. The project used historical and new data and included investigations both in the field and in the laboratory. A brief Pilot Study was conducted in the autumn and winter of 1975-76, followed by an extensive biological/chemical/physical survey in 1976-77 comparing the Buccaneer Gas and Oil Field area with adjacent undeveloped or control areas. In 1977-78, investigations were intensified within Buccaneer Gas and Oil Field, comparing conditions around production platforms, which release various effluents including produced brine, with those around satellite structures (well jackets) which release no effluents. In 1978-79, studies around Buccaneer Gas and Oil Field structures focused on (1) concentrations and effects of pollutants in major components of the marine ecosystem, including seawater, surficial sediments, suspended particulate matter, fouling community, bacterial community, and fishes and macro-crustaceans, (2) effects of circulation dynamics and hydrography on distribution of pollutants, and (3) mathematical modeling to describe and predict sources, fate and effects of pollutants. The final year, 1979-80, of study continued to focus on items (1) and (2) and on preparation of the milestone reports which represented the final products of this study.

This project has provided a unique opportunity for a multi-year investigation of effects of chronic, low-level contamination of a marine ecosystem associated with gas and oil production in a long-established field. In many respects, it represents a pioneering effort. It has been made possible through the cooporation of government agencies, Shell Oil Company (which owns and operates the field) and various contractors including universities and private companies. It is anticipated that the results of this project will impact in a significant way on future decisions regarding operations of gas and oil fields on the OCS.

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LIST OF REPORTS AND PUBLICATIONS

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1976-1977	Birds	78-0501
1976-1977	Ichthyoplankton	78-0501
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1976-1977	Plankton	78-0501
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1976-1977	Total Organics	78-0501
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1976-1977	Drift Bottle Releases	78-0501

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Year	Data Type	NODC Accession Number
1979-1980	Data being archived, will be available in late 1980	TBA

INTRODUCTION

Location of Study Area

The area selected for study is the operational Buccaneer Gas and Oil Field located approximately 49.6 kilometers (26.8 nautical miles) south southeast of the Galveston Sea Buoy off Galveston, Texas (Figure 1). This field was selected in 1975 as the study area because: (a) the field had been in production for about 15 years, which time had allowed full development of the associated marine communities; (b) it was isolated from other fields which facilitated the selection of an unaltered area (for comparison) within a reasonable distance of the field; (c) it produced both gas and oil that represented sources of pollutants from marine petroleum extraction; (d) its location simplified logistics and reduced the cost of the research; and (e) the Texas offshore area had not been fully developed for gas and oil production but was expected to experience accelerated exploitation in the future.

Operation History of Buccaneer Field

Buccaneer Field was developed by Shell Oil Company in four offshore blocks leased in 1960 and 1968 as follows:

Year	Lease Number	Block Number	Acreage	Hectares
1960	G0709	288	2,790	1,129
1960	G0713	295	4,770	1,930
1960	G0714	296	4,501	1,821
1968	G1783	289	2,610	1,056

In development of the field, 17 structures were built; two are production platforms, two are quarters platforms, and 13 are satellite structures surrounding well jackets. Initial exploratory drilling began about mid-summer of 1960 with mobile drilling rigs. When (as the result of the exploratory drilling) proper locations for platforms were selected, the permanent production platforms were constructed.

There have been no reports of major oil spills from this field. There have been some reported losses of oil due to occasional mechanical failure of various pieces of equipment. The largest reported spill was three barrels in 1973. The reported oil spill chronology and quantity for Buccaneer Field is as follows:

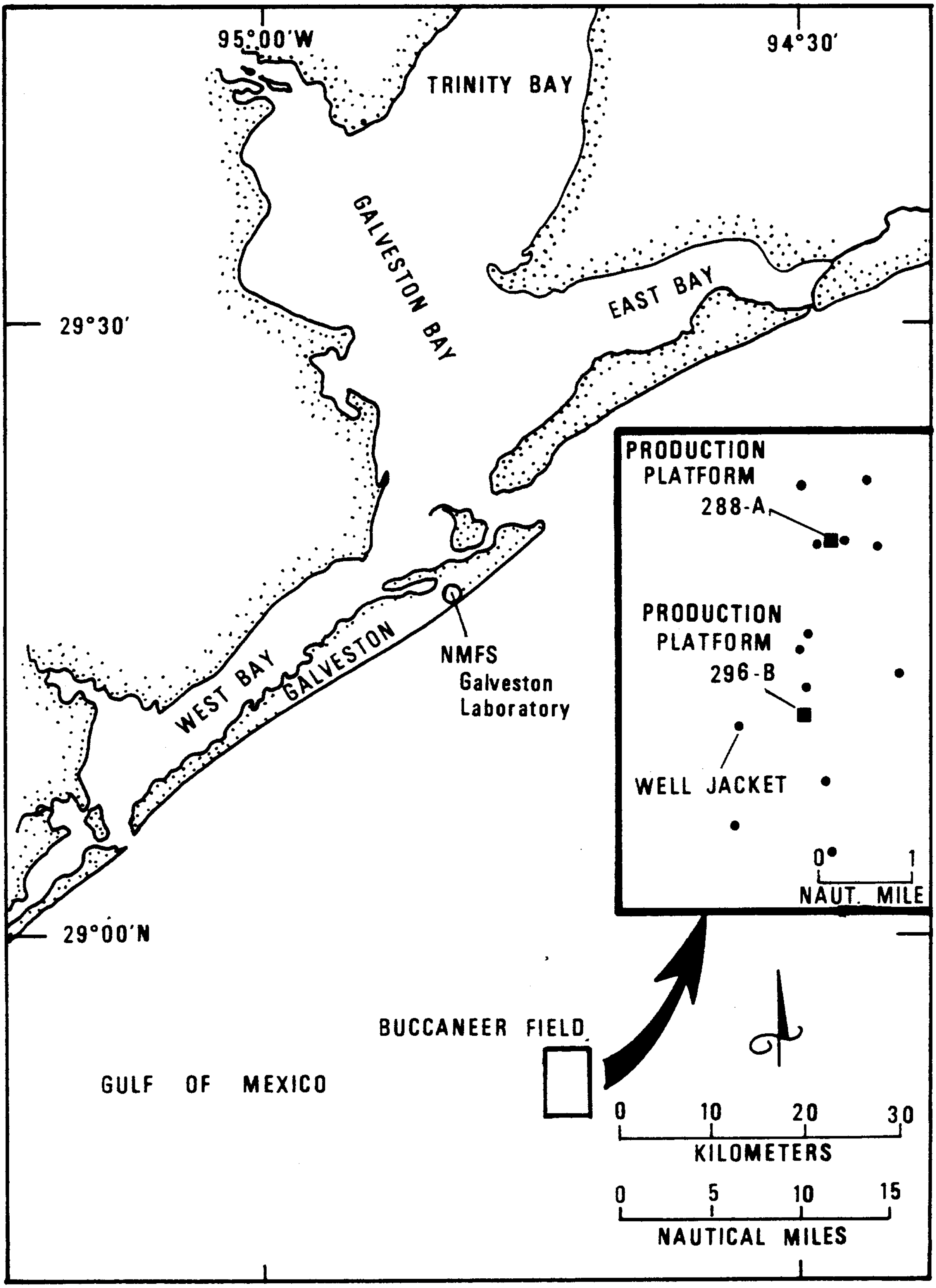

FIGURE 1. LOCATION OF BUCCANEER FIELD

Date	Source	Amount	
		Barrels	Liters
September 1973	Platform 296-B	0.5	79
November 1973	Unknown	3.0	477
July 1974	Platform 296-B	0.5	79
August 1974	Platform 296-B	1.7	265
September 1975	Platform 288-A	0.2-0.4	38-56
Totals		5.9-6.1	938-956

Buccaneer Field first began operations with the production of oil. Later, when significant quantities of gas were found, the field began producing both oil and gas and has continued to do so to date.

The production platforms and satellites (well jackets) are connected by a number of pipelines with a 50.8 centimeters (20-inch) diameter main pipeline connecting the field to shore. All of the pipelines that are 25.4 centimeters (10 inches) or greater in diameter are buried. The Blue Dolphin Pipeline Company was granted a pipeline permit (No. G1381, Blocks 288 and 296) in 1965 and has operated the pipeline since its construction.

Buccaneer Field occupies a limited area (about 59.3 km^2; 22.9 sq. statute miles) leased in the northwestern Gulf of Mexico. Four types of structures are located in Buccaneer Field: production platforms, quarters platforms, satellites (well jackets), and flare stacks. These are shown in Figure 2, which is an oblique aerial photograph of production platform 288-A and vicinity within Buccaneer Field. A map of Buccaneer Field, (Figure 3) depicts the locations of platforms and satellites within the field.

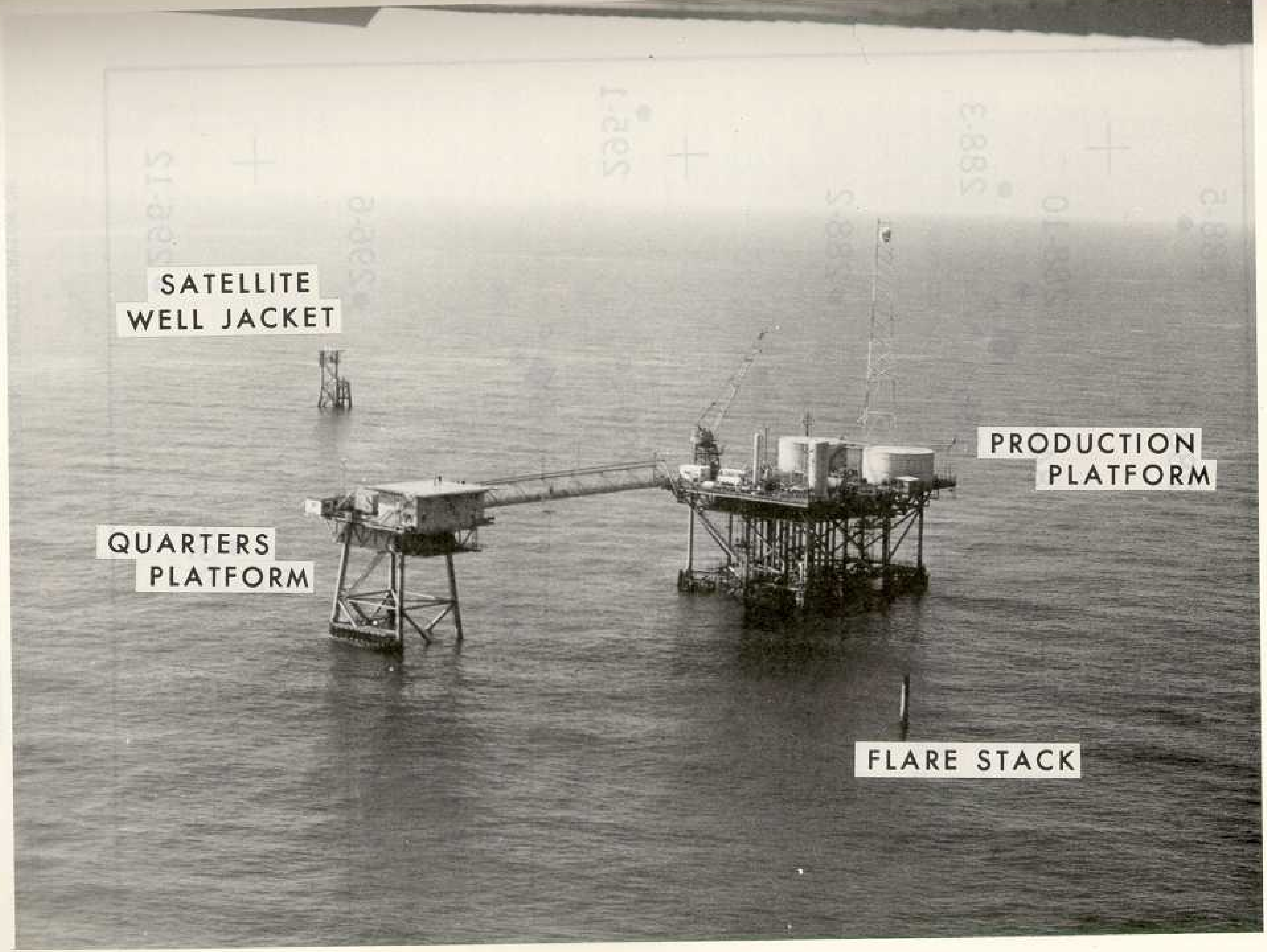

FIGURE 2. BUCCANEER FIELD STRUCTURES

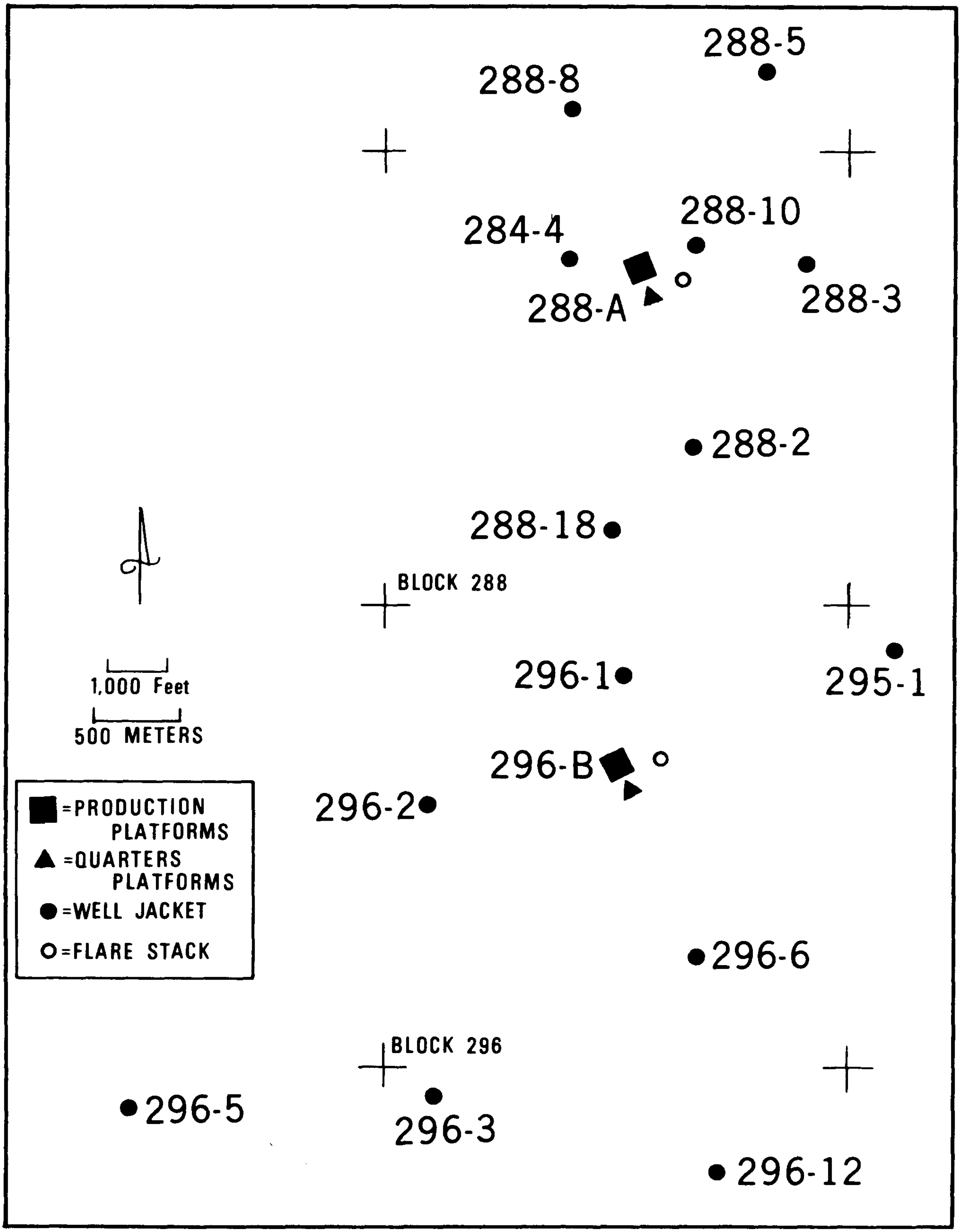

FIGURE 3. SHELL OIL COMPANY'S ALPHANUMERICAL IDENTIFICATION OF BUCCANEER GAS AND OIL FIELD STRUCTURES

WORK UNIT 2.3.9 - CURRENT PATTERNS AND HYDROGRAPHY OF THE BUCCANEER FIELD AND ADJACENT WATERS

NMFS Atlantic Environmental Group

R. S. Armstrong

ABSTRACT

This report presents a synthesis of results from four years of investigations in the Hydrodynamics Work Unit of the Buccaneer Gas and Oil Field Study. Goals of the Work Unit have been to describe the hydrographic conditions and circulation in and around the Buccaneer Field and to model the transport and dispersion of potential contaminants that may have been introduced into the marine environment from petroleum operations in the Buccaneer Field.

Water temperature records at the BGOF showed vertical stratification during spring and a weak, inverted structure during fall, with an annual cycle that closely paralleled air temperatures. Monthly means of air and surface water temperature at Galveston showed that the winters of 1977, 1978 and 1979 were among the coldest recorded in the last 40 years. Salinities were lowest in spring because of increased river discharge and a secondary minimum developed in fall because of shelf-wide current reversals at that time. The magnitude of the salinity decrease in spring indicated that much of the river discharge from rivers as far away as the Mississippi and Atchaflaya Rivers was carried past this region of the Texas shelf. During most of the year there was little or no density stratification, but in spring vertical structure was apparent when a layer of bottom water developed with low dissolved oxygen and decreased transparency.

Currents in and around the Buccaneer Field were typically directed alongshore with mean flow toward the southwest. Layered flow was seen to develop in late spring and summer when sub-surface currents reversed, flowing toward the east. Vector mean current speeds were about 15 cm/sec in the surface layer and about 10 cm/sec near the bottom. Scalar averaged current speeds were about 5 cm/sec greater. Current speeds were generally least in summer, highest in fall and almost as high in spring. Variability in the currents was greater in the alongshore direction than along the normal-to-shore orientation, with variability greatest at mid-depth and least near the bottom. Variance values for current meter records indicated that flow was most variable during fall and spring and steadiest in summer. The seasonal circulation pattern apparently resulted from broad-scale wind systems acting over the extent of the northwestern Gulf. However, during late spring, increased discharge from rivers of Louisiana and east-Texas caused flow in about the upper half of the water column to be directed to the southwest, contrary to the broad-scale wind-driven influence. Spectral analyses indicate that response of currents to local winds was associated mainly with the passage of atmospheric pressure patterns. Maximum currents measured during the BGOF Study (as high as 180 cm/sec) occurred following the passage of cold fronts. Variations in flow from tidal currents and from sea breeze winds were indicated in the current meter data. Predictive models were developed, based on observed conditions in the BGOF, to portray and for assessing the transport and dispersion of potential contaminants resulting from both instantaneous

and continuous releases and discharges. Different models were developed to represent dispersion for dissolved and suspended materials, surface film and floating contaminants, sinking particulate matter and re-suspended particles. Nomographs and charts or tables were made and concentrations for example inputs were derived and indicated that suspended/dissolved and floating/surface film discharges would be widely dispersed and rapidly diluted by the varying currents of the region. Accumulation of these fractions in the water could only occur with continuous discharge in the absence of wind and current, which might occur infrequently and persist for no more than perhaps two hours at a time. Particulate matter of size fractions coarser than fine sands would tend to accumulate essentially within the shadow of the platform from which they derived, size fractions down to medium silts would likely be distributed in thin layers out to about 5 km of the source and finer fractions would, on the average, be transported far afield before settling to the bottom. Events of re-suspension of surficial sediments by accelerated bottom currents was found to occur about 9% of the time, which implies that any accumulations of contaminants on the bottom would, before long, be re-suspended, and dispersed widely.

In general the models indicate that for any materials other than coarse particulates, the dynamic conditions in and around the Buccaneer Field are such that contaminants would be distributed widely and would be highly diluted.

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FIGURES

TABLES

SECTION I

INTRODUCTION

The impact on the marine ecosystem that may result from potential contamination from offshore petroleum development depends on the distribution and concentration of the contaminants, as controlled by the currents, hydrographic conditions and diffusive mixing processes, as well as by the nature and character of the pollutants. Assessments of impacts must take into account stresses on the biota because of the normal cycle of events in the environment and as may result from anomalous conditions that may have occurred during the period of investigation. As part of the four year, multi-disciplinary Buccaneer Gas and Oil Field (BGOF) study, investigations were conducted in the Hydrodynamics Work Unit, with the objectives of:

1. defining the hydrographic cycle of the waters of the BGOF,
2. describing the circulation pattern and the forces governing the currents,
3. developing predictive models of transport and dispersion of different classes of potential contaminants, and
4. providing physical oceanographic interpretations supportive of other projects in the BGOF study.

Studies in hydrodynamics during the first year were conducted by the Galveston Laboratory, NMFS/NOAA and focused on temperature and salinity observations and Lagrangian current measurements to determine the annual cycles and seasonal patterns (Martin 1977). Operations in the second year were carried out by the Atlantic Environmental Group, NMFS/NOAA and by Evans-Hamilton, Inc., Houston, Texas and were directed toward examining dispersion characteristics of the waters around the Field using a series of dye studies and further defining the circulation dynamics with Langrangian measurements and about a year of current meter data (Armstrong 1979 and Hamilton 1979). Two projects were conducted in the third year: Environmental Research and Technology, Inc., Houston, Texas developed dispersion models for predicting movements and concentrations of floating, sinking, and dissolved or suspended pollutants using data for the BGOF (Smedes et al. 1980); and Hazelton Environmental Sciences Corp., Northbrook, Illinois conducted detailed examinations of the hydrographic structure and currents at the BGOF from seasonal surveys and they analyzed sediment re-suspension dynamics (Danek and Tomlinson 1980). Projects carried out in hydrodynamics have been under Work Units 2.3.9 and 2.5.2.

This report covers studies in hydrodynamics conducted during the fourth year of the BGOF study, which have pursued the following objectives:

1. To summarize results from the previous three years of investigations in defining the hydrographic conditions and circulation dynamics.

2. To develop and employ models for describing the dispersion and transport of potential contaminants that may have derived from the Buccaneer Field.

SECTION 2

CONCLUSIONS

During the four years of investigations in hydrodynamics in the Buccaneer Gas and Oil Field Study, an extensive set of hydrologic data was collected or acquired and analyzed to describe the hydrographic conditions and circulation patterns in and around the Buccaneer Field. Results from these studies were applied to examine and model the dynamics for transport and dispersion of contaminants that may have derived from petroleum development and operations in the Field. In all, 15 months of current meter and anemometer records were compiled, 77 drifting buoys were deployed and tracked during 15 separate operations, and temperature and salinity measurements were made during 23 cruises. Historical, climatological data were compiled for considering anomalous conditions in the years of the BGOF Study and for examining driving force interactions for the waters. Specialized cruises were conducted to examine diffusion rates from dye dispersion studies and to measure waves, dissolved oxygen concentration, ph, suspended solids content and water transmissivity. Modeling projects were carried out using observed conditions in and around the BGOF to examine trajectories of transport and the dispersion and dilution that would result from the potential of both instantaneous and continuous releases of different classes of contaminants.

Water temperatures in the BGOF closely follow the annual cycle of air temperatures with minimum temperatures in January and annual maxima in July-August. Vertical temperature structure is apparent only in spring when surface waters are warming more rapidly than bottom waters, but, during October through January, a weak inverted temperature structure seems typical. Comparison of air and shore station water temperatures at Galveston for the period of the BGOF study, in comparison with historic records, indicates that the January-February periods of 1977, 1978, and 1979 were among the coldest of the last 40 years. The impact of these anomalously cold winters which occurred during the BGOF Study are uncertain, but should be considered in assessing the health of the marine ecosystem in the area.

The annual cycle of salinity at the BGOF exhibits a sharp drop to the annual minimum in May-June, reflecting spring increase in river discharge, and a secondary minimum in fall resulting from influx of brackish shelf water from the east as alongshore currents reverse at that time. The magnitude of salinity decrease in late spring implies that much of the discharge from rivers to the east, as far away as the Mississippi and Atchaflaya Rivers, is transported across this section of the Texas shelf. Salinities typically increase offshore, except in summer when only weak horizontal gradients occur, and vertical salinity gradients are distinct only in late spring at the Buccaneer Field. Significant vertical density stratification is apparent only in late spring when a bottom layer of water may develop of low oxygen content, elevated levels of suspended matter and low transparency. Limited sampling during other seasons indicates that for the rest of the year, the waters are nearly saturated with oxygen and are fairly clear throughout the water column.

Currents in and around the BGOF are typically aligned alongshore, with mean flow in the surface layer directed toward the southwest through most of the year. From mid-depth to the bottom, seasonal patterns develop, with flow toward the east and southeast in May-August and to the southwest for the remainder of the year, but with periods of mean eastward transport developing during winter. Vector mean current speeds in the data were of about 15 cm/sec in the surface layer, decreasing with depth to about 10 cm/sec near the bottom. Scalar averages of the current measurements were about 5 cm/sec greater at all depths. Current speeds were lowest in summer, highest in fall, and almost as high in spring.

The principal driving force for seasonal current patterns seems to be broad-scale wind patterns acting over the extent of the northwestern Gulf, with re-orientation of wind-driven transport by local bathymetry and coastline configuration. Response of the currents to local winds seems to be mainly associated with the passage of atmospheric pressure patterns at periods of 3-4 days in fall and winter (passage of continental air masses) and of about 8-1/2 days in spring and summer (development of maritime air masses). Maximum current speeds reported in the BGOF Study were as high as 180 cm/sec and occurred following the passage of cold fronts. During late spring the influx of fresh water from increased river discharge establishes flow to the southwest through about the upper half of the water column. Current variations resulting from astronomical tides and from the diurnal sea breeze also appear in the current observations. Variability in the current records was mainly aligned along an axis parallel to the coast, with variance magnitudes highest in fall, almost as high in late spring and lowest in summer or, implying that although current speeds are least in summer, currents may be steadier then.

Results from analyses of data collected or acquired in the BGOF Study were used to model and examine transport and dispersion characteristics of the waters for diluting potential releases of contaminants from the Buccaneer Field. Models were developed to consider distributional patterns and to compute dilutions that might be expected to result from both instantaneous and continuous discharges. Because of differences in dynamic response, types of discharges were examined separately as dissolved and suspended materials, floating and surface film contaminants, sinking particulates and as re-suspended particulate matter.

Portrayals and nomographs of the distribution and dilution of dissolved and suspended contaminants were developed from areal growth rate models to represent conditions as water dynamics progress from a static situation (no current) to the case of dispersion with a steady current to the circumstance of varying currents. Models for the first two cases were developed from dye study results and the last (varying currents), from computations of equal frequency ellipses by bivariate analyses of current meter records. For the static case, which might occur briefly when, for example, tidal currents oppose and cancel ambient currents, results indicated slow radial dispersion with concentrations at fixed distances from the source increasing at a rate proportional to the natural log of the length of time of continuing discharge. With a steady current, discharge would stream along the current trajectory with diffusion along the current direction at a rate about 3 times greater than that transverse to the current. With continuous discharge in a steady current and, since current speeds at the Buccaneer Field are typically 5 to 10 times greater than the rate of diffusion along the current direction, dispersion would principally be along a narrow plume with the current trajectory and accumulation could not occur. Concentrations would decrease rapidly downstream. Current meter and drifting buoy records show that, beyond a few hours, considerable variability in speed and direction develops in the currents. Results of analyses of current records for discharges continuing for lengthy periods, considering current variability, show widespread dispersion, particularly in the alongshore direction, and very rapid dilution. Dilution rates were somewhat lower near the bottom than through the rest of the water column. Charts of dilution magnitudes were constructed to portray distributions of contaminants resulting from long-term discharges and indicated weak net transport relative to dispersion by the varying currents, except in the surface layer where net transport would lead to a plume streaming toward the southwest.

Floating and surface film contaminants would be expected to be transported with the wind at about 3-1/2% of the wind speed. Depending on local wind conditions, it was found that such contaminants could reach the coast within about 2 days. To represent overall distributional patterns and dilutions resulting from continuous long-term discharges, equal frequency ellipses were calculated from annual variance values of anemometer data recorded at the BGOF, with magnitudes reduced by the 3-1/2% rule. Nomograph and dilution charts were derived for the case of long-term releases and showed very rapid dilution and widespread dispersion with somewhat greater dispersion toward the north than toward other directions.

Settling velocities for various size fractions of sinking particulates were determined from Stoke's law and, using the depth integrated mean current speed from current meter records at the BGOF (15 cm/sec), horizontal displacements for each size fraction before settling to the bottom were calculated. Results indicated that, on the average, particles coarser than fine sands would quickly sink to the bottom, typically accumulating within the shadow of the platform from which they derived. Particles finer than medium silts would behave essentially as suspended materials. Bivariate analysis of current meter data was used to determine depth integrated average equal frequency ellipses to estimate distributions of accumulations of continuously discharged particulates after settling to the bottom. As an example, with total release of 1 kgm/day continuing for a year, accumulated sinking particulates would be about 1 Micron thick at distances of 2 to 5 km from the source and at 100 m from the source, thickness would be 200 Microns, or less.

Consideration of sediment distributions at the Buccaneer Field indicated that the occurrence of bottom currents in excess of 26 cm/sec would lead to re-suspension of surficial sediments, including particulate contaminants that may have derived from Field operations and settled to the bottom. Wave action was concluded to be of only minor importance for re-suspension, except during severe storms when wave energy might lead to considerable reworking of sediments. From hourly current meter observations at the BGOF, near bottom currents exceeded speeds of 26 cm/sec 9% of the time, with seasonal differences in frequency of occurrence indicating low likelihood of re-suspension and transport of settled contaminants in summer and high likelihood during fall. Typical speeds and durations of events when near bottom currents exceeded 26 cm/sec imply that re-suspended particulates would be transported 6 km or more during each re-suspension event.

SECTION 3

MATERIALS AND METHODS

An extensive set of hydrologic data was collected in the projects of the Hydrodynamics Work Unit of the BGOF Study. Various portions of the data were collected by Hazelton Environmental Sciences Corp., the Galveston Laboratory of NMFS and the Atlantic Environmental Group of NMFS. In addition, about a year of current meter and anemometer data collected in the Ocean Current Measurement Program* were made available for the BGOF Study (Hamilton 1979).

Hydrographic observations were collected on 23 cruises conducted between May 1976 and May 1979. Water temperature and salinity measurements were made on all cruises. Dissolved oxygen concentration, pH, water transparency and suspended solids were measured during four seasonal cruises in 1978-1979. Both Lagrangian and Eulerian techniques were used to examine circulation dynamics in and around the Buccaneer Field. A total of 77 drifting buoys were released and tracked from land by radio direction finding during 15 separate operations conducted between July 1976 and April 1978. Eulerian measurements came from 15 months of current meter records (December 1975-December 1976 and during July-August 1978 and February-March 1979). Currents were measured at three depths (near surface, mid-depth, and near bottom), and wind measurements were taken during the same periods. Detailed structure of the currents was obtained from a profiling current meter used at six to seven stations in the Field during four seasonal operations in 1978-1979. Further information on the dynamics was obtained from two months of wave measurements in July 1978 and in February 1979. A series of three seasonal (summer, fall, winter) dye studies were conducted in 1977-1978 to measure dispersion characteristics of the waters. Climatological data sets were also acquired to examine the correspondence of the hydrologic conditions to these forces and influences (river discharge data from the U.S. Army Corps of Engineers and the U.S. Geological Survey, air temperature records, Galveston Weather Station from the National Weather Service, and shore station water temperature records (Galveston) from the National Ocean survey).

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* The Ocean Current Measurement Program was conducted by Evans-Hamilton, Inc., Houston and sponsored by Shell Development Co., Exxon Production Research Co., AMOCO Production Co., Mobil Research and Development Corp., and Chevron Oil Field Research Co.. Currents and winds were recorded from instruments at Platform 288-A of the Buccaneer Field.

For analyses of the hydrodynamics of the Buccaneer Field, the hydrographic and circulation data have been compiled to describe annual cycles and for defining the driving forces and controlling influences. Information on the currents and results from the dye studies were used to estimate, describe, and form predictive models of transport and dispersion characteristics of the waters. Most of the models used are based on computing dilution resulting from rate of area enlargement of discharge plumes.

SECTION 4

RESULTS AND DISCUSSION

HYDROGRAPHY

The annual cycle of surface and bottom temperatures at the Buccaneer Field are shown in Figure 1. Water temperature cycle, as observed in 1976-1979, closely paralleled air temperatures, reaching maximum values in July-August of about 30°C at the surface and about 29°C at the bottom. Minimum water temperatures (about 12°C) occurred in January. Vertical temperature structure exhibited a pattern of inverted gradient for October through January (bottom waters about 0.5°C warmer than at the surface) and, for April through August, the surface waters were about 1°C warmer than the bottom water. Typically, there was little or no vertical temperature structure in February and September.

As compared to monthly mean air temperatures at Galveston Weather Station, averaged for the 37 months of the BGOF observations (May 1976-May 1979), surface water temperatures were about the same as air temperatures for March through September and were about 4° to 5°C warmer than air temperatures during November through January. Air temperature-water temperature comparisons were variable for February and October. Comparison of monthly mean air temperatures (Galveston Weather Station) for the three years of the BGOF observations with long-term monthly means (1940-1979) indicates that air temperatures for May 1976-May 1979 were within 2°C of normal for all months except January and February. In January, for 1976-1979, air temperatures averaged about 4°C cooler than normal and the February mean was about 3° below normal. In fact, monthly mean air temperatures for the three Januarys of the BGOF sampling (1977, 1978, 1979) were the three coldest of the 40-year record, all three Februarys were below normal and February 1978 was the coldest of the 1940-1979 period. Water temperatures at the beach at Galveston record only one January in the 57-year record that was colder than each January of 1977-1979 and Februarys of 1977-1979 were below the long-term average with February 1978, the coldest of record (monthly mean sea-surface temperatures from tide station, Galveston, from National Ocean Survey/NOAA). The cycle of water temperatures shown in Figure 1 are probably representative of normal conditions for April through December, but are probably below normal for January through March.

Unusually low temperatures were observed at the Buccaneer Field in July 1977 (Figure 1). Observations in late June and early August of 1977 were typical. Although the cause of the cool water in July in unclear, it seemed to be associated with a tongue or cell of low salinity water emanating from the northeast.

Horizontal temperature gradients in the waters in and around the Buccaneer Field were found to be complex, probably reflecting local variations in currents (Danek and Tomlinson 1980), but generally trend toward higher temperatures offshore.

Salinity observations collected near Platform 288-A of the Buccaneer Field are shown in Figure 2, compiled to show the annual cycle. Minimum salinities in surface and sub-surface waters occur in late spring, with a secondary minimum in fall. The minimum in late spring has been shown in data collected in 1963-1965 and attributed to the spring increase in river discharge from the Mississippi and Atchaflaya Rivers, with about a two month lag, and from the Trinity and Sabine Rivers, with about a one month lag (Temple et al. 1977). Salinity decrease during fall also appears in the 1963-1965 data for stations along the upper Texas coast. The fall decrease in salinity apparently results from the seasonal reversal in currents which transports freshened water from the east into the area of the Buccaneer Field. During fall, river discharge is at or near the annual minimum.

Horizontal salinity gradients around the BGOF typically increased offshore, although during summer, the trend could be reversed with small increases in salinity toward shore (Danek and Tomlinson 1980). Salinity data collected in May 1976 through May 1979 in the Buccaneer Field indicated that salinities increased with depth, but only weakly so, except during late spring, when more significant salinity structure was apparent.

Temperature and salinity observations from the BGOF Study indicate that significant density stratification develops in the Field only in late spring (May-June). Measurements in May 1979 (Danek and Tomlinson 1980) indicate that because of density stratification, a bottom layer of water may develop in spring which is low in dissolved oxygen content (about 50% saturated) and is of low transparency because of suspended matter. Throughout the rest of the year the waters are nearly saturated with oxygen and are quite clear throughout the water column. The pH data showed generally homogeneous conditions horizontally and vertically and displayed no seasonal differences.

CURRENTS

Compilation of the Lagrangian (drifting buoys) and Eulerian (current meters) current measurements collected and acquired for the BGOF Study (Figure 3) indicates that the currents are typically aligned alongshore and exhibit distinct seasonality, with some layering of contrasting flow in late spring and during summer. Mean currents in the surface layer were found to be directed downcoast (to the southwest) throughout the year, but with an offshore component during summer. Flow at mid-depth to the bottom was directed upcoast and offshore, (toward east and southeast) in May-August and generally directed downcoast, to the southwest, for the remainder of the year, but with periods of eastward currents during winter.

Current speeds typically decreased with depth, with vector mean speeds of about 15 cm/sec in the surface layer and about 10 cm/sec near the bottom. Scalar averaged current speeds were about 5 cm/sec greater. Seasonally, current speeds were generally least in summer, highest in fall, and almost as high in spring.

During the second year of the BGOF Study, the forces governing the water circulation were examined (Armstrong 1979). It was found that daily fluctuations are associated with local winds, but mean flow patterns result from broad-scale wind patterns acting over the extent of the northwestern Gulf with wind-driven transport re-directed by the local bathymetry and coastline configuration. During spring and early summer, increased river discharge from streams as far away as the Mississippi River causes the currents through about the upper half of the water column in the Buccaneer Field to be directed to the southwest, in opposition to the wind-driven transport of the prevailing winds. In fact, using BGOF data for 1976, the total discharge of the Mississippi and Atchaflaya Rivers during peak discharge that year (March-April average) plus the discharge from the Sabine and Trinity Rivers (using April-May average), for a combined discharge rate of 26.5 x 10^3 m^3/sec, could be accommodated by a stream 75 km wide flowing at the vector mean speed in the upper 10 m recorded at the BGOF in May, calculated so as to account for the salinity decline that occurs at the BGOF in May (decline of 6 ^{o}/oo from April, Figure 2), and assuming river discharge volume at 0 ^{o}/oo salinity. This example implies that in late spring, a large portion of the discharge from all rivers extending eastward to the Mississippi River is carried past the area of the continental shelf around the Buccaneer Field.

Spectral energy diagrams of BGOF anemometer and current meter records were generated (Hamilton 1979) and analyzed (Armstrong 1979) and indicated dominant periods in both records at one day, 3-4 days and about 8-1/2 days. The one-day period was considered to be the sea breeze, and the other two frequencies were concluded to be associated with passage of atmospheric pressure patterns of continental origin in fall and winter (3-4 day period) and of maritime origin during spring and summer (8-1/2 day period). Longer periods of more than two weeks were also indicated in both the wind and current data. A peak in the current meter spectral energy diagrams at the period of astronomical tides was also apparent. Maximum currents measured during the BGOF Study were as high as 180 cm/sec and were found to occur following the passage of cold fronts.

Variability of currents in the Buccaneer Field, which affects dispersion of potential contaminants, is mostly in the alongshore direction (alongshore variance in current meter records about twice the magnitude of normal-to-shore component). Variability in the 1976 current meter data was greatest at mid-depth levels and least near the bottom. Seasonally, variance magnitudes were highest in fall, almost as high in late spring months, and lowest in summer. Spectral energy analyses of the current meter records indicate that tidal currents and wind shifts account for most of the flow variability.

DISPERSION AND TRANSPORT OF POTENTIAL CONTAMINANTS

For dynamic considerations, pollutants that may enter the waters from petroleum operations would be of the form of either (1) dissolved and suspended contaminants, (2) floating and surface film pollutants, (3) sinking, particulate matter, or (4) re-suspended, sediment material.

Dissolved and Suspended Materials

Dye studies, conducted in conjunction with drifting buoy deployments in the BGOF Study indicated that dissolved and suspended substances are transported with the current, and spreading rates are greatest along the wind and current direction and least transverse to the current (Armstrong 1979). Axial spreading rates of point source releases were linear with time and did not seem to vary with tidal current reversals. Averaged spreading rates amounted to $\pm$70 m/hour along the current direction and $\pm$25 m/hour transverse to the current, with current speeds of about 12 cm/sec. The dye plumes were generally elliptical in shape. Dye study results indicated that discharge from the BGOF quickly mixes to a depth of about 10 m and does not go deeper. To estimate the transport and dilution of potential contaminants in dissolved and suspended form, four classes of conditions were modeled:

a. Discharge without currents --

Least spread and dispersion, and highest concentrations in the local environment, would develop in a case without wind or current. For such a situation suspended and dissolved substances would diffuse in a circularly spreading plume which undergoes no net transport. Although such events are highly unlikely in the Buccaneer Field, conditions approaching this circumstance may develop for brief periods. Using the spreading rate transverse to the wind and current, derived from the dye studies (25 m/hr), as a realistic approximation for radial dispersion in a static situation, dilution, concentration, and spread magnitudes can be estimated. For this estimation, it is assumed that all discharged material becomes homogeneously distributed through the upper 10 m of the water and never penetrates deeper. It is also assumed that as the discharge plume expands radially another 25 m each hour, 1/t (t : time in hours) of an hour's discharge disperses into this expanded ring, with 1/t of that discharge volume accumulating with later discharge in each inner ring. Example results of plume dimensions, dilutions, and resulting concentrations are listed in Table 1.

TABLE 1. DILUTION AND EXAMPLE CONCENTRATIONS OF DISSOLVED AND SUSPENDED MATERIALS FOR CONTINUOUS DISCHARGE WITHOUT CURRENTS

Discharge Duration	Discharge Plume Dimension (Radial distance from source)	Average Dilution (per m^3)		Average Concentration* of Pollutant with discharge of 1 kgm/hr (gm/m^3)	
		Outer Edge of plume	Within 25 m of source	Outer Edge of plume	Within 25 m of source
1 hour	25 m	---	$5.1x10^{-4}$	---	$5.1x10^{-2}$
3 hours	75 m	$3.4x10^{-5}$	$9.3x10^{-4}$	$3.4x10^{-3}$	$9.3x10^{-2}$
10 hours	250 m	$2.7x10^{-6}$	$1.5x10^{-3}$	$2.7x10^{-4}$	0.15
30 hours	750 m	$2.9x10^{-7}$	$2.0x10^{-3}$	$2.9x10^{-5}$	0.20
100 hours	2500 m	$2.6x10^{-8}$	$2.7x10^{-3}$	$2.6x10^{-6}$	0.27

* Assuming discharged material homogeneously mixed through upper 10 m of water column.

At the rates shown in Table 1, it would take about 10 weeks for the discharge plume to reach the coast (about 40 km away), where dilution would be about $10^{-12}/m^3$ and, using the example in Table 1 of continuous discharge of 1 kgm/hr, contaminant concentration at the coast would be about $10^{-10}gm/m^3$. In this case, with continuous discharge, concentrations at fixed distances from the source would increase at a rate proportional to the natural log of length of time of discharge.

b. Instantaneous release with currents --

This model deals with the case in which a single release occurs, e.g., an accidental spill. Dye studies which were conducted in the BGOF Study simulate this situation with a plume developing and spreading as it is transported along a current trajectory away from the source location. Based on the dye study results, Environmental Research and Technology, Inc. developed a hydrodynamic model in the BGOF Study to describe the movement and concentrations that would develop from an instantaneous, point source release of suspended and dissolved materials (Smedes et al 1980). Using sample sets of current meter data from the Buccaneer Field, collected in summer and winter, they ran sample calculations from the model. Results showed little seasonal difference of significance, except for seasonal differences in mean current direction. These test runs with the model indicated that, for the case of an instantaneous release from a platform in the BGOF of 1 kgm of contaminant, which instantly becomes evenly distributed through the upper 10 m of the water column, the material would be transported along a current trajectory and, by the time the resulting plume departs the shadow of the platform, concentrations would be about 1 gm/m^3 (10^{-2} dilution factor); after 2 hours, the plume would be located about 1 km downstream with concentrations of about 0.1 gm/m^3 (10^{-3} dilution) in a plume some 100 to 200 m wide, and after 48 hours, the plume would be about 1 km wide, located about 10 km downstream and concentrations would be reduced to about 10^{-4} gm/m^3 (10^{-6} dilution).

c. Continuous discharge with steady current --

This model represents the condition in which dissolved and suspended contaminants are discharged continuously, or sporadically for lengthy periods, and are transported and dispersed by a non-varying current. By tracking the growth and spread of a dye plume as it progresses along a current trajectory, we can determine dispersion for continuous discharge with a steady current. Averaging results from the three dye studies conducted in the BGOF Study indicates that after an hour of continuous discharge, contaminants would be stretched along a strip 0.45 km long (0.45 km/hr average current); at the head, dispersion would spread the material 25 m to both sides of the current trajectory and 70 m downstream, in advance of the current vector, in a semi-elliptical shape. Since the dye studies indicated that these dispersion dimensions increase linearly with time, for at least a few hours, the plume resulting from the hour's discharge would extend in a triangular shape from the elliptical head back to the discharge point for the apex of the triangle. The area encompassed by this plume after an hour would be $1.4x10^4$ m^2, giving a dilution of $7.1x10^{-5}m^{-3}$. Assuming, for example, a release of 1 kgm of contaminant in the hour, and assuming that this material is homogeneously spread through the upper 10 m of the water, and that currents and dispersion are invariant through the upper 10 m, then after an hour, the average concentration within the plume would be $7.5x10^{-3}$ gm/m^3. Since the current speed is greater than the rates of dispersion, accumulation near the source cannot occur. (The 0.45 km/hr current speed, from dye study conditions and used above, is less than, or about equal to, mean scalar current speeds at all depths from the current meter records of the BGOF.)

If, after an hour of discharge, release of contaminants stopped, then the plume would be transported away from the source with the current and enlarge by dispersion. Each succeeding hour, assuming continued linear spreading, the plume would expand ± 25 m laterally and ± 70 m longitudinally to the current vector. The areal growth of the plume each hour would be defined by a series of concentric, egg-shaped rings, as we follow the plume. If we assume that during each successive hour, 1/t (t : time in hours) of the pollutant disperses into the enlarged ring area, then we can calculate progressive dilution at distances outward from the center of the plume. Computed dilutions at distances radially away from the center of the plume (along the current direction and transverse to the current) resulting from an hour of discharge, and for continuing discharges for other time increments, are shown in the nomograph of Figure 4. For curves in Figure 4, it was assumed that the dilution at half the radial distance across a ring equalled the average dilution value for that ring.

d. Continuous discharge with varying currents --

Observations in the Buccaneer Field indicate that the currents are not steady but vary considerably in speed and direction. As evidenced in the preceding discussion, dispersion of dissolved and suspended materials is much more rapidly accomplished by spreading along a current vector than by mixing around the vector. Therefore, the distribution and dilution resulting from continuous discharge from a point source can be fairly well determined if we can define the areal distribution of the time-varying current vectors.

The distribution of current vectors at the Buccaneer Field can be estimated from the statistical compilations of the year's worth of hourly current meter data recorded in 1976 (Hamilton 1979). Using the method of bivariate analysis with variance and co-variance values of alongshore (NE-SW) and normal-to-shore (NW-SE) components of the currents, components of equal frequency ellipses were calculated, using tables of F-test for Equality of Variances with derived eigenvalues (characteristic roots). This approach allows calculating axial magnitudes and axes orientation of a series of concentric ellipses, each of which would be expected to include a certain proportion of the current vectors (F-test confidence regions), assuming normal distributions in the data. The concept is that after an appropriate period of time, the currents would have transported and dispersed a percentage of continuously discharged material over the area encompassed by that confidence percentile ellipse. Dilution values for a depth level can be calculated by dividing the area within a percentile ellipse into that percent of a unit area. Dilution computations used here were for elliptical rings (differences between pairs of concentric ellipses.) The resulting value of dilution for a ring was taken to be the value at mid-distance, axially, across the ring. Axial distances for dilution values are measured away from the net displacement (mean current vector) position and, therefore, refer to a moving coordinate system.

Since the axial components of confidence ellipses are in units of speed, multiplication by time (ellipse axes and unit area for dilution calculations) gives dilution at distances away from the center of the discharge plume for various periods of continued discharge. Nomographs of dilution for variance values for the whole year's records for the current meters at 4 m, 10 m and 18 m were developed. Figure 5 is shown for the currents at 4 m depth. Curves drawn in Figure 5 are for dilution along the principal axes of the confidence ellipses, with the major axis aligned approximately alongshore, and in the direction of mean transport and the minor axis directed generally normal-to-shore. Curves for 4 m and 10 m depths were nearly identical, but dilution along the major axis near the bottom, at 18 m, was only about 1/2 as much as in the upper waters.

The current meter data used above only represents the Eulerian field of motion and conditions within the Buccaneer Field. To test the validity of using these results in a Lagrangian sense and outside the Field, confidence ellipses and dilutions were calculated from the records of daily movements of all of the drifting buoys deployed around the Field and tracked for distances as far away as about 150 km. Dilution curves derived from the buoy movements were very similar to those for the 4 m and 10 m current meter records; therefore, it is considered that the results from the current meter data are representative for conditions of dispersion over much of the continental shelf off eastern Texas.

However, dilution values from the 4 m and 10 m current meters, as exemplified by Figure 5, indicate about a 20 times greater dilution along the current direction and about 3 times greater transverse to the mean current as compared to the results derived from the dye study measurements for the case of dispersion along a steady current trajectory (Figure 4). With continuous discharge it should be expected that, for the first 2-3 hours, dispersion and dilution of dissolved and suspended contaminants should proceed similar to that depicted for a steady current (Figure 4). At longer periods currents begin to vary and, after a year, features as in Figure 5 from the current meter data should be more appropriate. Therefore, a combination from these two models should give the most realistic depiction. As an intermediate condition between the steady current and the annual variance in the current meter records, dilution curves were developed by the method of bivariate analysis using averages of monthly values of variance in the current meter data. Annual values showed about two-fold greater dilution than did the monthly mean values. From these three sets of curves (annual and monthly mean current meter variance and dye study interpretation) combination dilution nomographs were constructed (Figure 6, for upper waters) to depict dilution of continuous discharge as dynamic conditions in the waters change from a state characterized by steady flow, persisting for 2 hours, to one of varying currents.

If we know the rate of discharge of dissolved and suspended material and the resulting vertical distribution in the water column, concentrations resulting from continuous discharge can be estimated from the dilution nomographs. Concentration values from the nomographs are calculated by multiplying the hourly rate that the contaminant is introduced into a 1 m depth layer by the dilution value, from the nomograph, with concentration in units of discharged contaminant units per m^3. Distances in the dilution charts are measured along and normal to the net transport (mean current vector). For example, with discharge of dissolved and suspended contaminant at a rate of 1 kgm/hr and assuming this material becomes evenly distributed through the upper 10 m of the water column, then the contaminant would be introduced at the rate of 100 gm/hr into each 1 m depth layer. From Figure 6, after 1 hour, concentration would be 1.9×10^{-3} gm/m^3 (1.9×10^{-5} m^{-3} dilution) at distances of 270 m downstream and 25 m lateral to the net transport location after the hour, and following the curves for 1 hour of discharge, concentration of 10^{-5} gm/m^3 (10^{-7} m^{-3} dilution) would occur at distances of 1.3 km along and 0.65 km transverse to the mean current, as measured away from the net transport location. After a week of continuous discharge at this discharge rate assuming the mean current is parallel to the coast, concentrations of about 5×10^{-7} gm/m^3 (5×10^{-9} m^{-3} dilution) should be expected along the coast 40 km lateral to the current.

From Figure 6, and its counterparts for 10 m and 18 m depths dilution maps can be constructed, for a system of currents. Using the annual mean vector currents from the current meter records of 1976 (12.1 cm/sec at 4 m depth, 3.3 cm/sec at 10 m and 1.3 cm/sec at 18 m, directed toward west-southwest at 4 m and toward southwest at 10 and 18 m, from Hamilton 1979) distribution maps of dilution levels were constructed to represent the conditions resulting from continuous discharge of dissolved and suspended contaminants (Figures 7-9). Dilution levels over the area shown in Figures 7-9 would develop within about one week. Since the patterns shown in these maps would develop within a week but were derived from annual means of currents, the distributions shown should not be expected to actually occur. However, the features indicated of rapid and wide dispersal, without accumulation should be representative and realistic. Spreading is indicated to be mainly alongshore throughout the water column.

Floating and Surface Film Pollutants

As part of the modeling study, conducted by Environmental Research and Technology, Inc. in the BGOF (Smedes et al 1980), the transport and dispersion of instantaneous releases of surface-borne contaminants was examined. They concluded that wind drift was the principal driving force with transport at 3-1/2% of the wind speed and in the same direction as the wind. They found distinct differences in trajectories of surface-borne materials, because of seasonal wind patterns and that floating contaminants could well reach the coast within about two days, under the right wind conditions.

To consider the pattern and distribution of surface-borne materials resulting from continuous discharge, a dilution nomograph was constructed, using the method of bivariate analysis with annual values of variance listed in Hamilton (1979) for hourly wind observations at the Buccaneer Field in 1976. The procedures used in developing the dilution nomograph were the same as employed with current meter data in the preceding subsection, except that axial components computed for confidence ellipses of winds were reduced by 3-1/2%, following the conclusions drawn by Smedes et al (1980) for surface layer, wind drift. The dilution curves and values were similar to those for the 4 m current meter record of Figure 5, except that values along the major and minor axes were almost equal (confidence ellipses almost circular). Using 3-1/2% of the annual vector mean wind (6.7 cm/sec) for a transport vector, a dilution chart was constructed (Figure 10) to display the average distribution of floating and surface film contaminants that might be expected from continuous release, based on the annual variability of wind drift.

The pattern in Figure 10 indicates that widespread dispersion is typical, but with mean southerly winds, northerly transport toward land would be typical.

Sinking Particulate Contaminants

Another modeling project conducted in the BGOF Study by Environmental Research and Technology, Inc. involved estimating distances from the source required for particulate matter to settle to the bottom, after transport by the currents (Smedes et al. 1980). From Stoke's law they derived settling velocities for particulates by size fractions, ranging from fine sands to clay size particles. Expanding on these results, sinking times for particles of each size fraction to reach the bottom (20 m) can be calculated and, for a given current speed structure, the horizontal distances these particles would travel before settling to the bottom can be computed. Resulting settling velocities, sinking times and horizontal displacements for fine sand to clay size particles are listed in Table 2. Horizontal displacements in Table 2 were calculated using an average current speed for the water column of 15 cm/sec (depth integrated, scalar mean speed of BGOF current meter records of 1976). From Table 2, particulate contaminants coarser than fine sands probably sink to the bottom and accumulate almost directly below the discharge and particles finer than medium silts would behave essentially as suspended material.

The techniques used for dissolved and suspended materials involving bivariate analysis of current meter records can be employed to estimate accumulations of continuous or frequent, sporadic releases of sinking, particulate contaminants that could be expected from dispersion and transport by the varying currents in the BGOF. As an example of potential distributions, the cumulative thickness of the layer of settling particulates that would result from one year of continuous releases at the rate of 1 m^3/day of all size fractions was calculated. For these calculations it was assumed that the influx was comprised of equal volumes of each of the 7 size fractions listed in Table 2, so that 52 m^3 of each size fraction was released into the waters during the year. Distributional pattern of current variability was defined from depth integrated averages of confidence ellipse axes from the annual variance of the current meter data at 4 m, 10 m and 18 m depths. Net transport was computed as the depth integrated average of the annual, vector means of the current meter data. Values of sinking time to reach the bottom, in Table 2, were then used to calculate, for each size fraction, the thickness of particulate accumulation on the bottom after a year at distances from the source of input. Total accumulation of all sinking particulates (thickness of contaminant sediments) was found by adding the contributions by each size fraction. The resulting distributional pattern that might be expected for this example of continuous release of particulates at the rate of 1 m^3/day, and continuing for a year, is shown in Figure 11, for the area in which accumulated settling particle thickness is 1 Micron or greater.

For the example depicted in Figure 11, accumulated thickness would be less than 1 Micron at distances from the source of more than about 5 km downstream (toward the southwest), 4 km upstream (northeast) and 2 km to the southeast and northwest. Settling particles within the 1 Micron thickness region of Figure 11 would be comprised almost entirely of coarse silts and larger fractions. The pattern of dispersion shown in Figure 11 and the results listed in Table 2 indicate that except for coarse size material, sinking particulate contaminants would be distributed widely and at low concentrations.

TABLE 2. SETTLING RATES AND TRANSPORT OF SINKING PARTICULATE CONTAMINANTS

Particle Size (microns)	Mean Settling Velocity 1) (cm/sec)	Sinking Time to Bottom-20 m (hours)	Horizontal Displacement 2) (km)
>120 (coarse fractions)	>1	<0.5	<0.3
120 (fine sand)	1.0	0.56	0.3
60-100 (very fine sand)	0.462	1.20	0.65
20-60 (coarse silt)	0.136	4.08	2.1
6-20 (medium silt)	1.43×10^{-2}	38.9	21
2-6 (fine silt)	1.36×10^{-3}	408	210
<2 (clay)	6.8×10^{-5}	8170	4300

1) From Smedes et al. 1980.

2) Computed for average current = 15 cm/sec (depth integrated, mean scalar speed for BGOF current meter records, from Hamilton 1979).

Re-suspended Sediments

Particulate contaminants that have settled to the bottom become available for redistribution and transport by re-suspension. Divers in the BGOF Study have reported fairly frequent instances of decreased transparency in the water because of re-suspension of sediment material. As the energy of water motion exceeds some threshold condition, sediment fractions would be brought back into the water column to be transported by the currents. As part of the investigation conducted by Hazelton Environmental Sciences Corp. in the BGOF Study, re-suspension dynamics by accelerating currents and by wave action were examined (Danek and Tomlinson 1980). They concluded that currents, rather than waves, were the principal cause of re-suspension in the Buccaneer Field, although under strong storm conditions, considerable re-working of sediments could occur. Based on sediment size distributions around the Field, they estimated that bottom currents in excess of about 26 cm/sec were necessary to accomplish re-suspension of surficial sediment particles. Potential for bottom currents in excess of 26 cm/sec can be determined from current meter data recorded at 18 m in the BGOF Study. Currents were measured near the bottom from March-October, 1976 (Hamilton 1979) and for a month during each July-August 1978 and February-March 1979. For all these records, currents were >26 cm/sec 9% of the time (hourly observations), with frequencies of occurrence of about 5% for February-March, 15% for April-June, near zero in July-September, and 33% in October.

In the current meter records, near bottom currents at speeds >26 cm/sec typically persisted for periods of 6 hours or more with average speeds during the event of about 30-40 cm/sec. Except in summer, when bottom currents rarely exceeded 26 cm/sec, the currents were normally directed toward the southwest. Therefore, with these conditions, during each re-suspension event, sediment material would be transported about 6-8 km or more to the southwest before settling to the bottom again.

These results imply that during summer, some accumulation of particulate contaminants might develop around the area but, during the rest of the year, any accumulations of other than coarse size material would be widely distributed and would be transported well away from the source.

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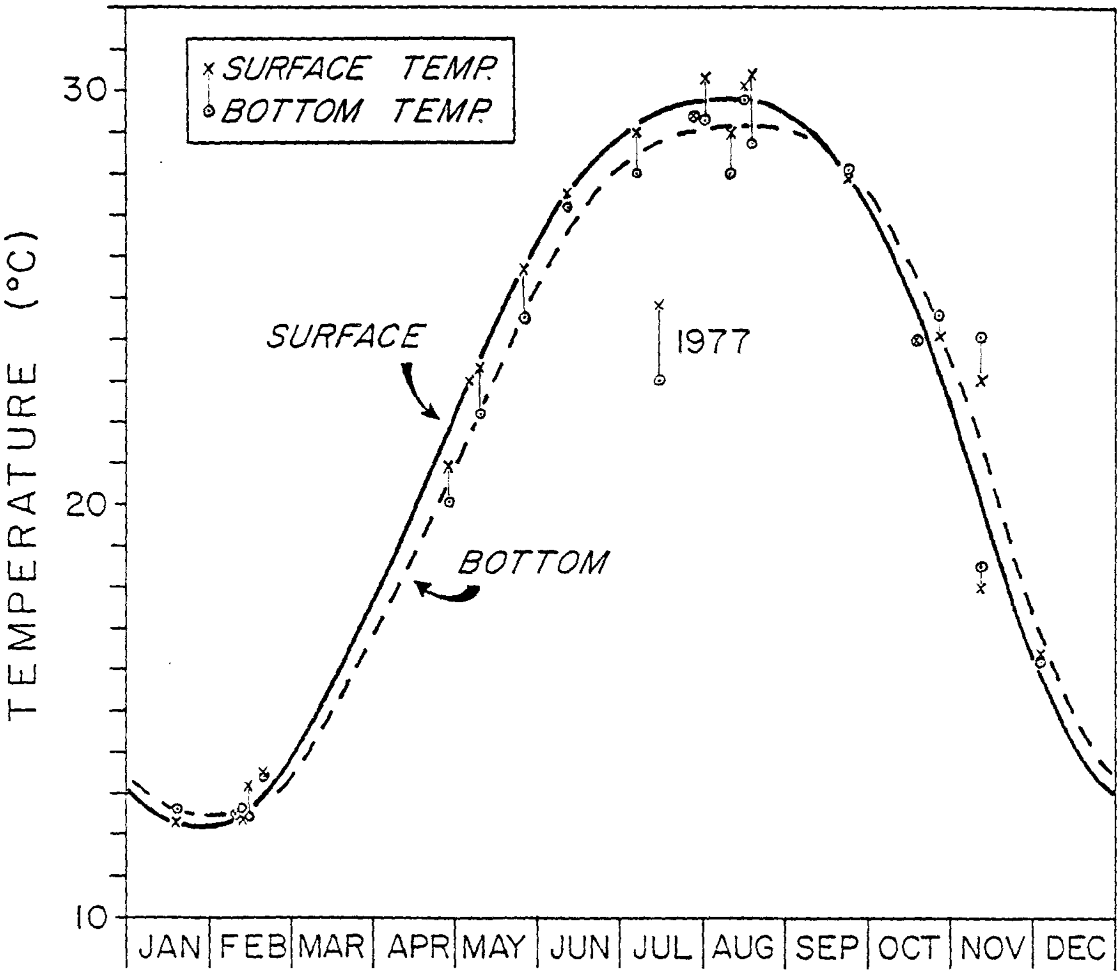

Figure 1. Water temperature in the BGOF, 1976-1979.

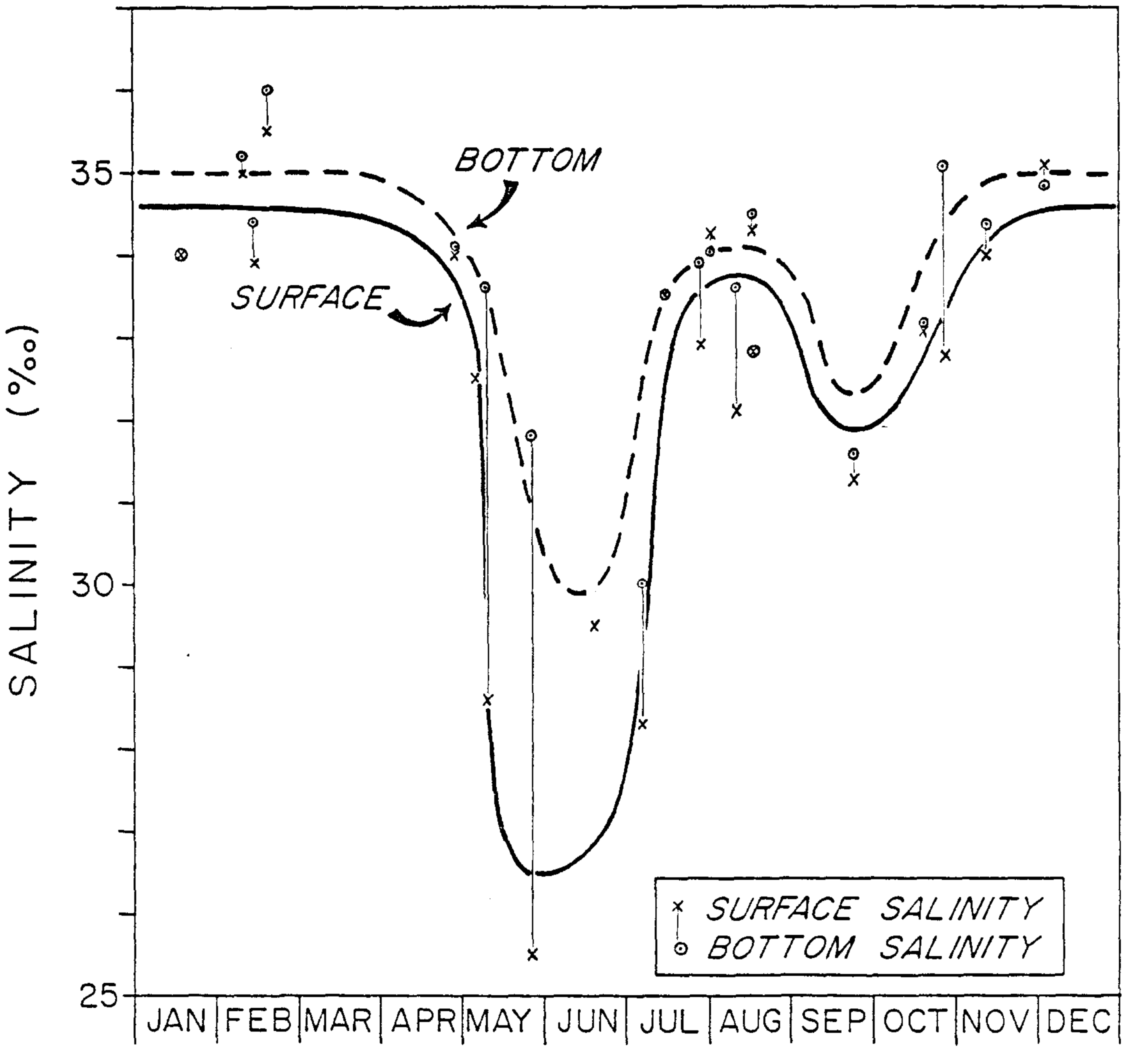

Figure 2. Salinity in the BGOF, 1976-1979.

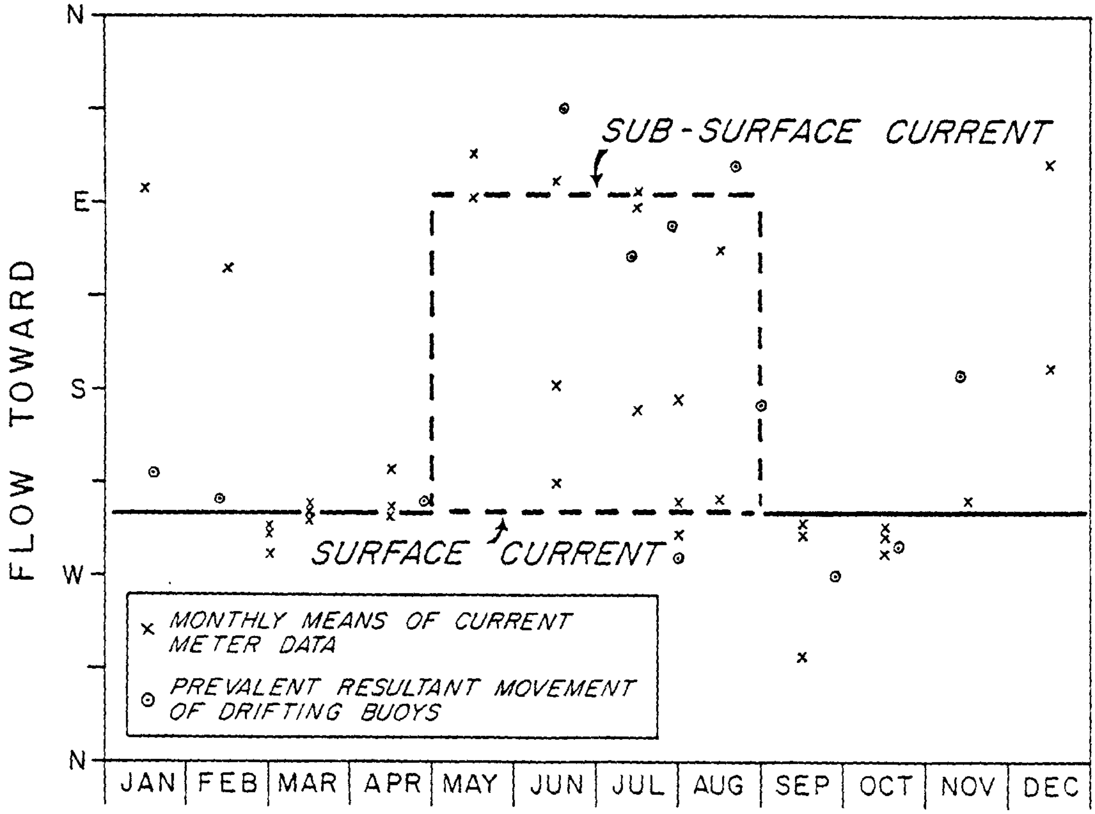

Figure 3. Mean current direction in the BGOF, 1976-1979.

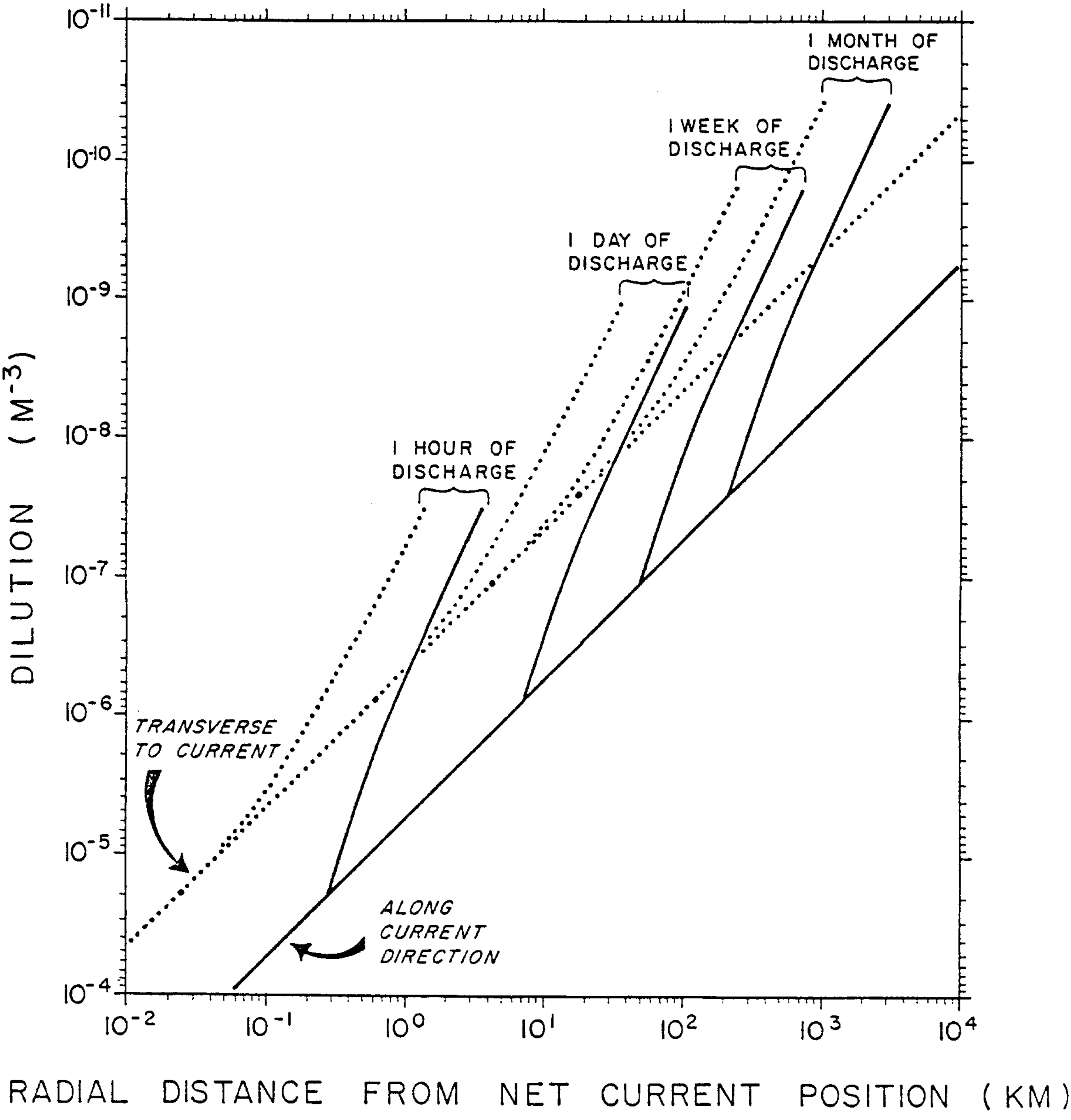

Figure 4. Dilution of dissolved and suspended materials at the BGOF resulting from continuous discharge with steady current.

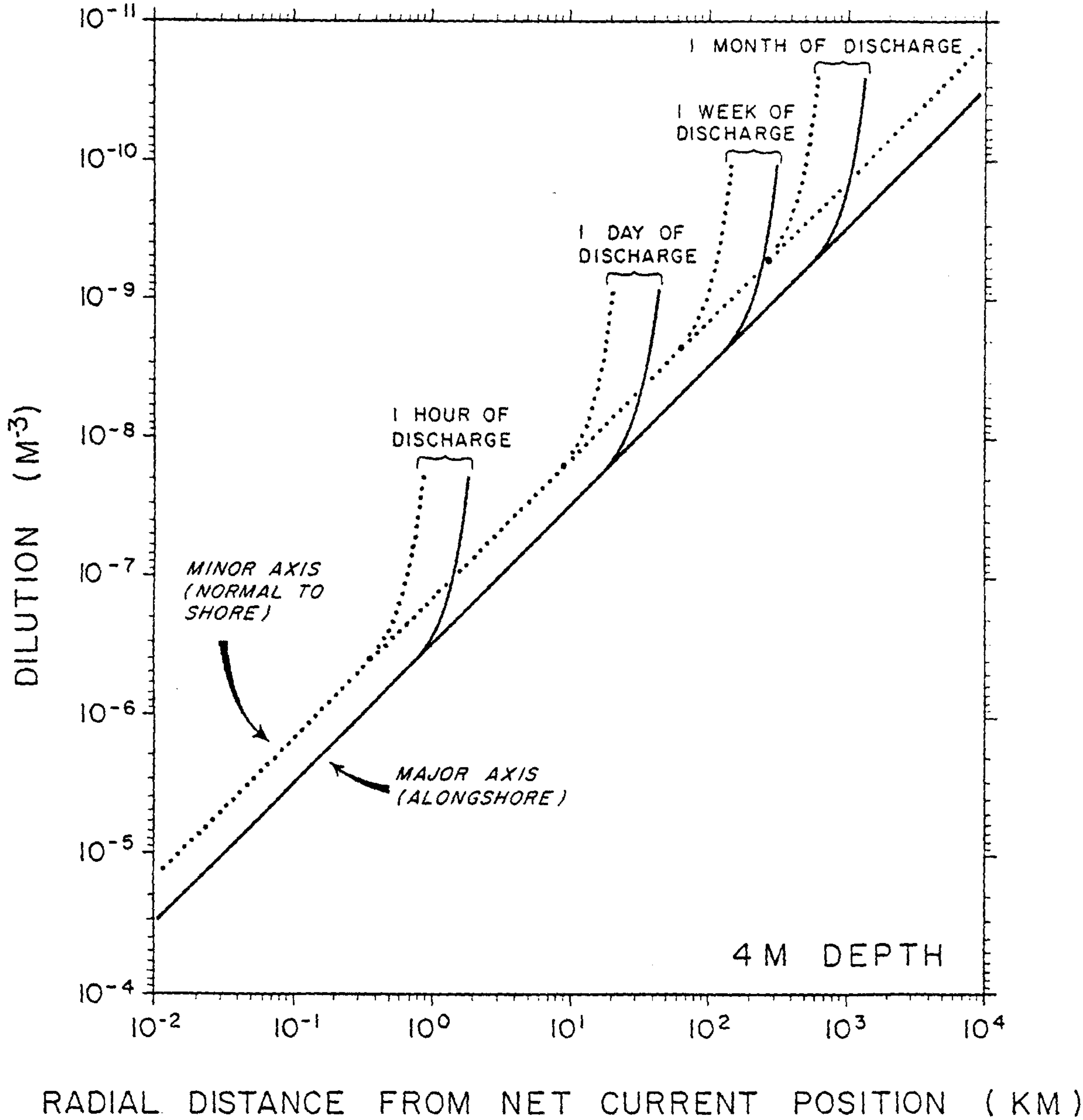

Figure 5. Dilution of dissolved and suspended materials at the BGOF resulting from continuous discharge with annually varying currents.

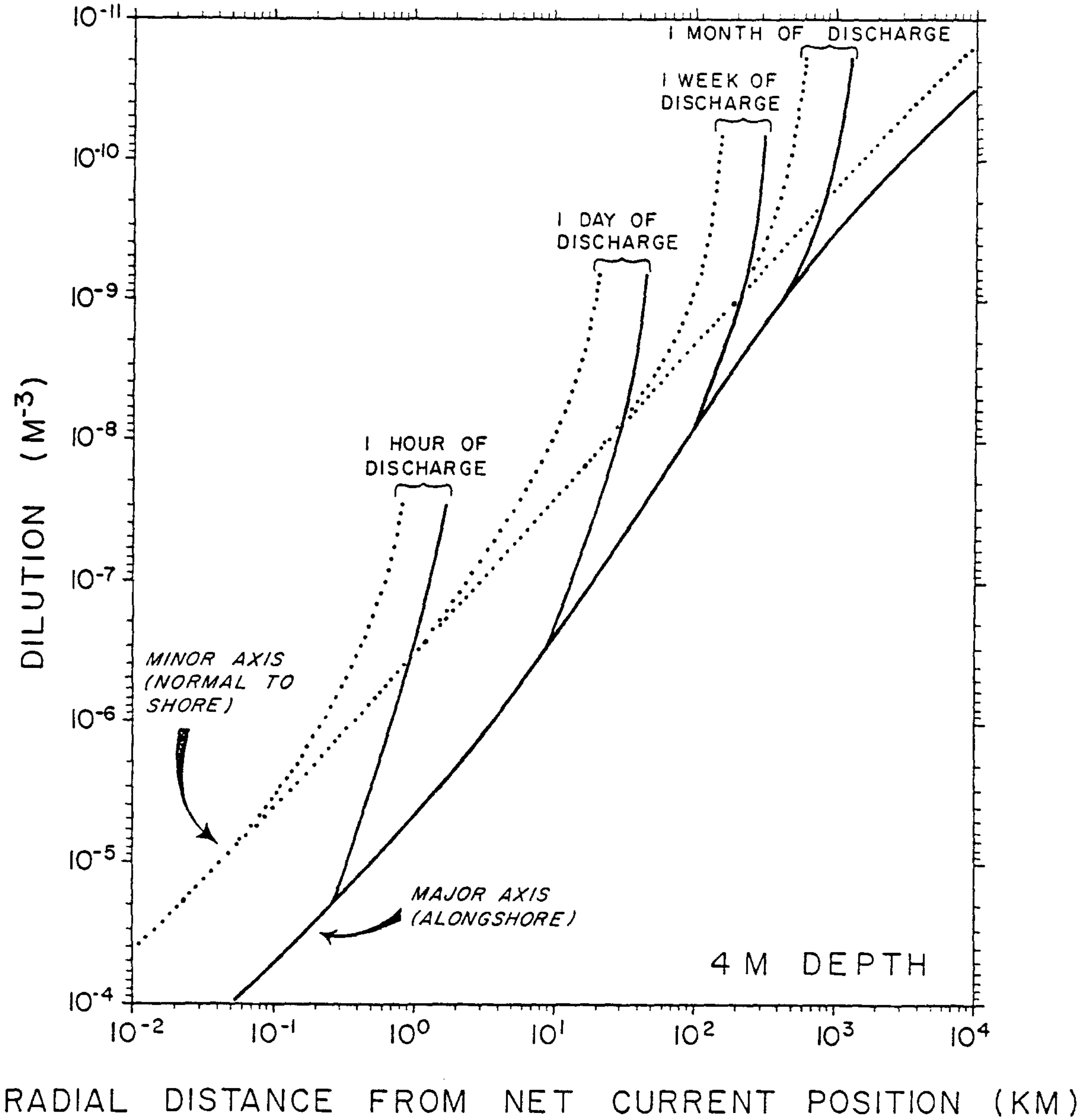

Figure 6. Dilution of dissolved and suspended materials at the BGOF resulting from continuous discharge as currents shift from steady flow to annually varying flow.

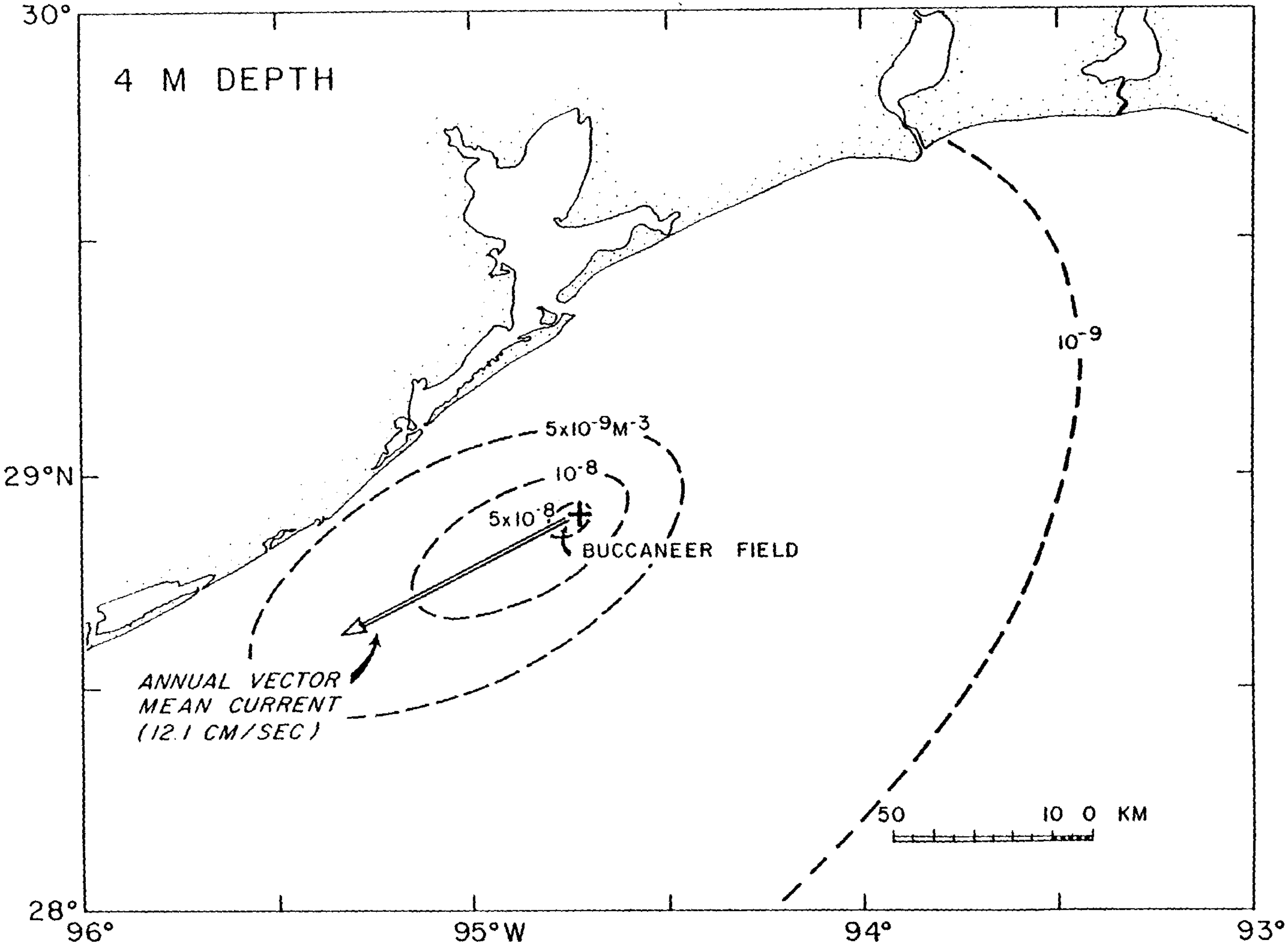

Figure 7. Annual pattern of movement and dilution of dissolved and suspended materials with continuous discharge (4 m depth).

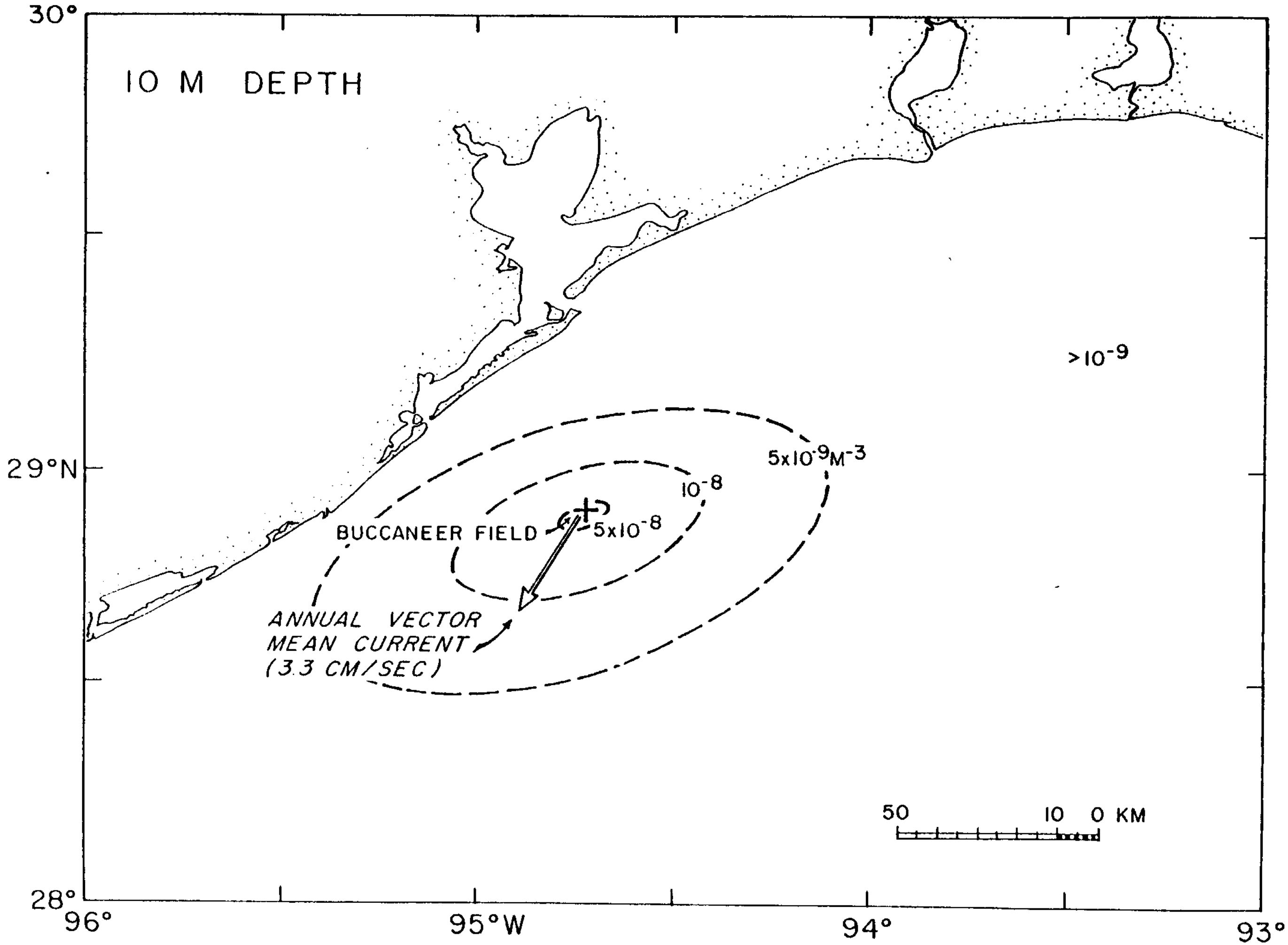

Figure 8. Annual pattern of movement and dilution of dissolved and suspended materials with continuous discharge (10 m depth).

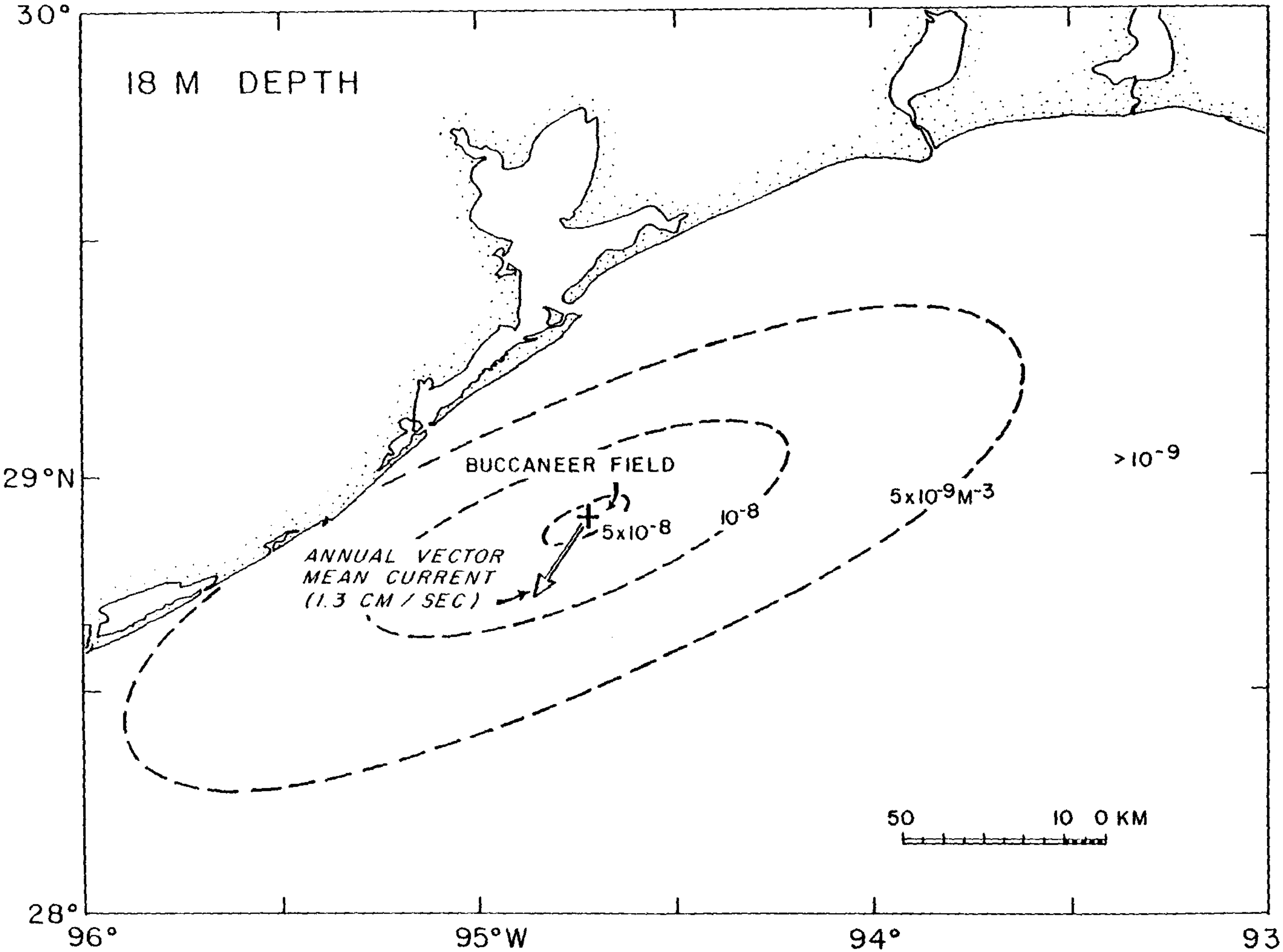

Figure 9. Annual pattern of movement and dilution of dissolved and suspended materials with continuous discharge (18 m depth).

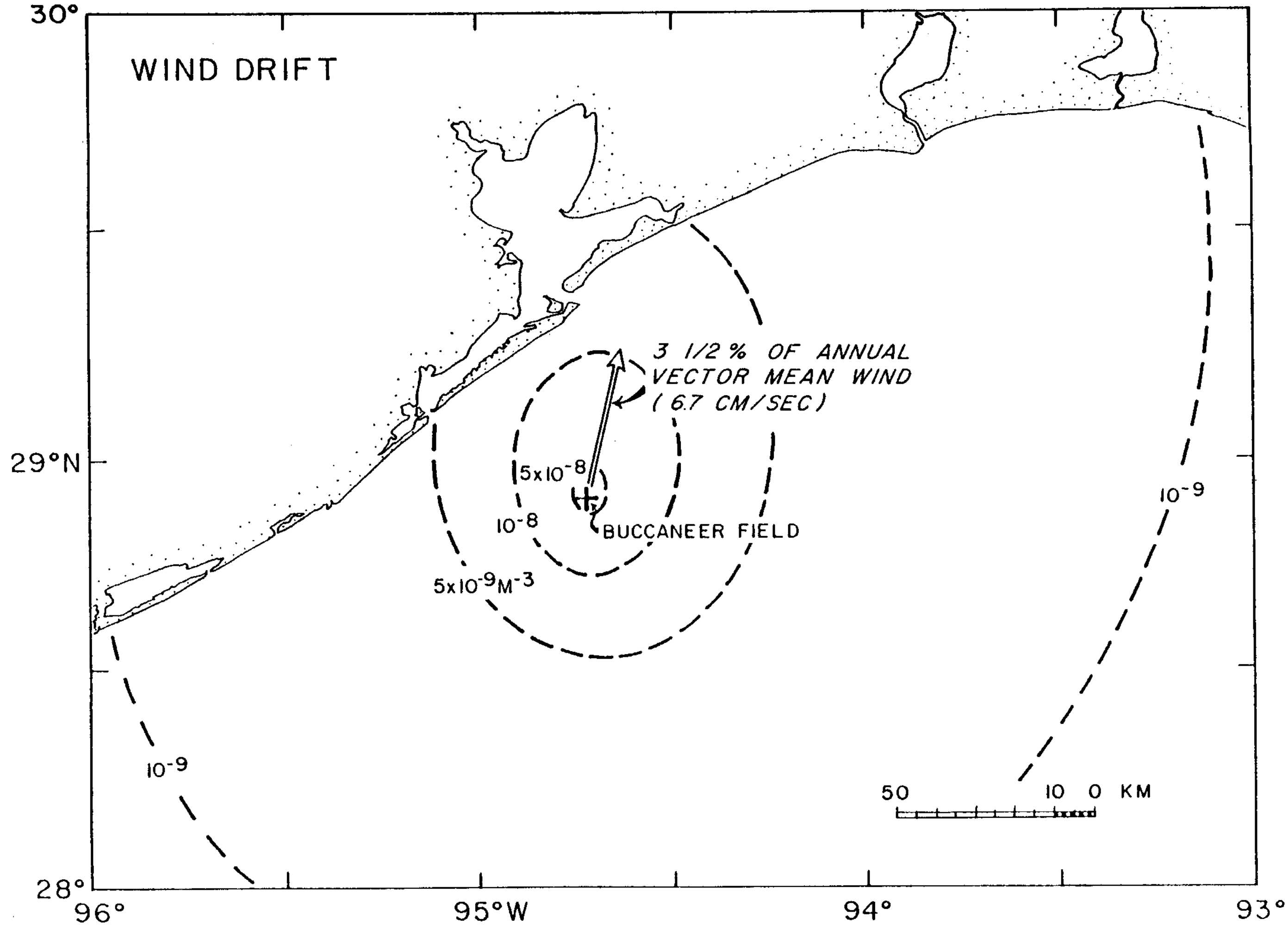

Figure 10. Annual pattern of movement and dilution of floating and surface film releases with continuous discharge (wind drift).

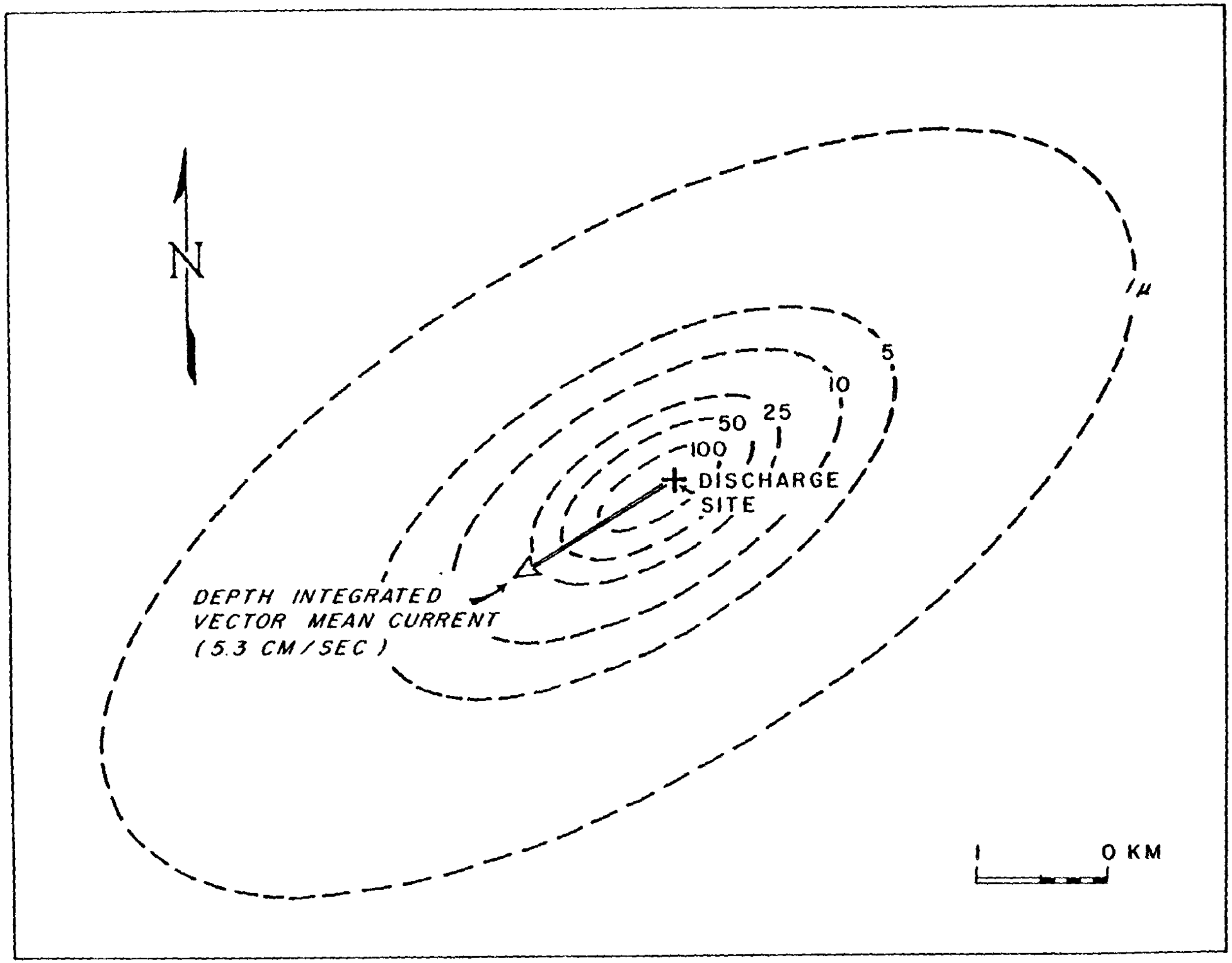

Figure 11. Accumulated thickness on the bottom of sinking particles after 1 year of continuous release at rate of 1 kgm/day.